Integration of Renewable Energy Resources into the Distribution Network - A Review on Required Power Quality

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Abstract

Power quality is the critical element of modern power system network where more and more distributed energy resources (DER) can be found. Distributed generation, generates electricity from many small DER particularly from renewable sources. Distributed generator (DG) within the network from renewable energy resources (RER) like solar and wind, bring significant challenges to maintain acceptable power quality (PQ) at the consumer end. This paper investigates PQ issues associated with RER. It reviews existing PQ standards for distribution network (DN) and also summarized the experiences of several Distributed Network Service Provider (DNSP) while integrating DGs into the grid. It was found that few PQ parameter ranges varies in different standards due to lack of harmonization and that may hinder to accept bulk renewable energy into the grid.

Keywords

Power Quality; Solar; Wind; Storage; Standard; Distribution Network

Introduction

Power is the rate of energy which is proportional to the product of voltage and current. PQ is the set of defined limits of electrical properties to ensure continuity of service and allows electrical systems to function in desired manner. PQ disturbances occur in magnitude and waveform of frequency, voltage, and current and may results in failure or improper operation of end equipments. PQ problems can originate in supply system, customer's end or in neighbouring installation. End users are more vibrant in PQ issues and better informed about interruptions, sags, swells, and transient switching. Many electrical applications are now interconnected and any PQ issues may have adverse consequences on other applications as well. New generation microprocessor or controller based load equipment and power electronic devices are more sensitive to PQ. The deviation in performance characteristics of small generating sources such as distributed generators (DG) can cause PQ deviation in the distribution network (DN).

However substantial increase of interest developed for DG, especially integration of electricity from Renewable Energy (RE) sources into the power system network through low voltage (LV) DN. The characteristics of RE sources influence the output electricity which is quite variable with time and different than the grid power characteristics, moreover RE sources does not guarantee load and demand management. Therefore, there are a number of PQ issues that must be addressed before integrating DG into the power network and regulatory standards play an important role to ensure power qualities. Alternating current (AC) power systems are designed to operate at a sinusoidal voltage of a given frequency (typically 50Hz or 60Hz) and magnitude. Also there is always a close relationship between voltage and current in any practical power system component. This paper considers solar photovoltaic (PV), wind turbine and storage as DGs and reviewed different available international and Australian standards in integrating DGs into the DN in Australia. By investigating different standards a clear gap in synchronization was found among various PQ parameter ranges which need to be coordinated before integrating bulk number of DG into the DN.

Background

Two most promising DGs are solar PV and Wind turbine. PV array considered as a device that produces DC electricity in direct proportion to the global solar radiation and can be calculated by Equation 1[1-2].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)[1+\alpha_P (T_C - T_{C,STC})] \qquad (1)$$

where Y_{PV} - rated capacity of PV array, meaning power output under standard test conditions [kW]; f_{PV} - PV de-rating factor [%]; G_T - solar radiation incident on PV array in current time step [kW/m^2]; $G_{T,STC}$ - incident radiation under standard test conditions [1 kW/m^2]; α_P - temperature coefficient of power [%/^{o}C]; T_C - PV cell temperature in current time step [^{o}C]; $T_{C,STC}$ -PV cell temperature under standard test conditions [25^{o}C]. Performance of PV array depends on de-rating factors like temperature, dirt and mismatched modules.

Kinetic energy of wind can be converted into electrical energy by using wind turbine, rotor, gear box and generator. Wind turbine can convert maximum 59.3% of the kinetic energy of the wind into mechanical energy which is known as Betz limit or "power coefficient" and the value is: C_P= 0.59. The output of wind turbine can be calculated [3] as per Equation 2:

$$P = \frac{1}{2} C_p \rho A V^3 \qquad (2)$$

where, P is Power output from wind turbine in Watts, ρ is the air density (1.225kg/m^3 at 15^{o}C and 1-atmosphere or in sea level), A is rotor swept area in m^2, V is the wind speed in m/s.

The basic characteristic of solar radiation and wind speed directly influences the output from PV array and wind turbine. Equation 1 and 2 showed that PV output is directly proportional to the solar radiation and wind turbine output is proportional to the cubic of wind speed. Daily profile of solar radiation and wind speed shows that these sources cannot support the load according to the load demand rather generates energy according to the weather condition also unable to generate any output when sun does not shine and wind does not blow. This situation can cause voltage rise or drop at different time of the day. Figure 1 and 2 shows the solar radiation and wind speed of highly potential locations in Australia [4]. Moreover sudden fluctuation in solar radiation or wind speed also causes fluctuation in the output power.

However consumers load demand varies with usage patterns and consumer class such as residential, commercial or industrial class as shown in the Figure 3 [5]. Moreover load demand also varies with seasonal effect. Therefore there is a clear gap in renewable energy generation and load demand which could be managed by energy storage systems.

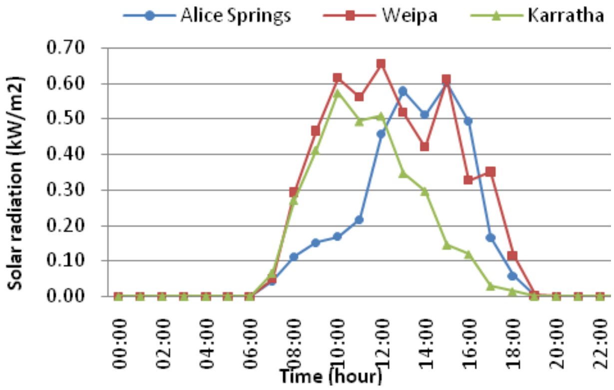

FIGURE 1 SOLAR RADIATION IN THREE POTENTIAL LOCATIONS IN AUSTRALIA[4]

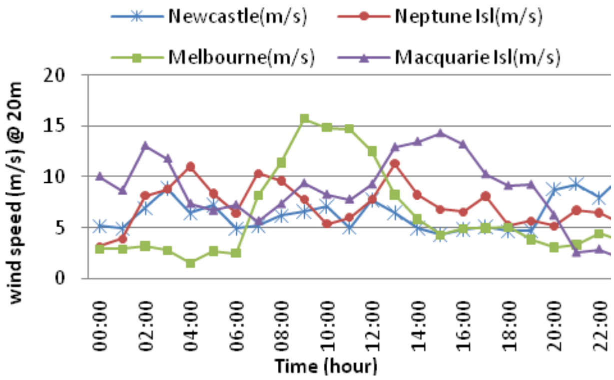

FIGURE 2 WIND SPEED AT FOUR POTENTIAL LOCATIONS IN AUSTRALIA[4]

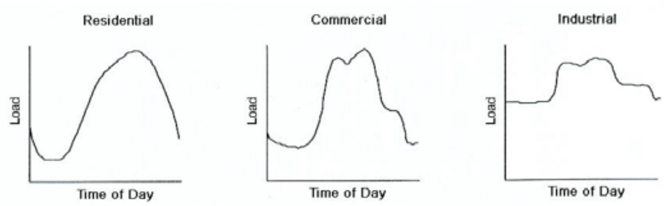

FIGURE 3 TYPICAL CUSTOMER LOAD PROFILE[5]

Traditionally, electric power grid was operated with several large generating units supplying power to the transmission grid towards the load. The introduction of DG changed this scenario by integrating many DGs to the LV DN as shown in Figure 4. These DGs are expected to be mostly owned and operated by individuals. The nature of DG connected near the load introduces power flow in both directions at the point of common coupling (PCC) and large scale integration of such DGs have influences on system reliability and PQ. A Grid-Tie Inverter (GTI) converts Direct Current (DC) electricity from DGs into Alternating Current (AC) and feeds into the grid at PCC. A pure sine wave inverter ideally produces a perfect sine wave, however in practical applications there will always be some harmonic distortion as a result of the conversion process.

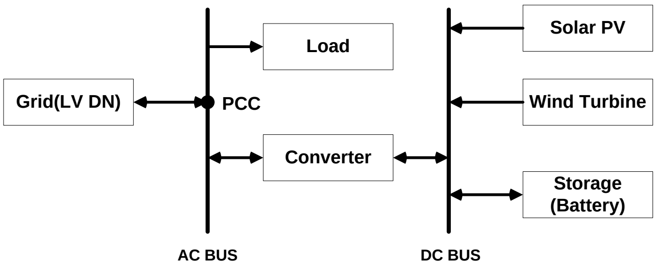

FIGURE 4 CONNECTION OF DGS INTO THE LV-DN

It was mentioned in [6] that integration of large scale wind turbines have impacts such as steady state voltage rise, over-current, flicker emission during continuous operation or switching operation, voltage drop, harmonics, power system oscillation and voltage stability problems. While integrating large scale photovoltaic (PV), irregular solar radiation by passing clouds could introduce power and voltage fluctuations at the PCC [7]. However mismatch between PV modules, inverter, filter, controller and other power electronics injected harmonics into the grid at the PCC. Energy storage used to improve PQ for transient problems such as voltage drop, fluctuations. However for long time storage functions in energy management may have significant influence from the associated inverter and power electronics.

Generally, change in load consumption reflected in voltage drop or rise which is a great concern for DG. The connection of DGs into the grid may introduce phase unbalance by unloading one phase compared to the other. The inherent characteristics of solar and wind energy may introduce voltage drop or rise and flicker. Power electronics with these sources along with storage system and frequent switching operation may introduce harmonics. Therefore before integrating large scale solar, wind and storage into the grid existing PQ standards needs to be reviewed for consistent, efficient operation and best use of RE. The most common PQ indicators and influences of DGs on these indicators are described in next section. After that different regulatory standards are illustrated indicating several PQ parameter limits.

Power Quality

Power quality has emerged as a major area of electric power engineering due to the increased sensitivity of end-use equipment. Network operator cannot keep the supply exactly at the ideal level due to different types of disturbances and PQ problems, when these disturbances exceed the allowable range. Poor grounding/earthlings introduces neutral-to-grounding voltage rise also interruption occurs where supply lost completely. Power factor is also an important feature. Different PQ indicators are described below:

Voltage Sags and Swell

If the supply voltage becomes much lower (<90% of nominal voltage) or if becomes much higher (>110% of nominal voltage) and last for long time (> 1 minute) than it is called under-voltage or over-voltage respectively [8]. Short term such variations (<1 minute) are called sags (between 10% and 90% of nominal voltage) and swell (>110% of nominal voltage) respectively [9] as shown in Figure 5. Sag and swell a power system disturbance in which r.m.s. supply voltage fall/rise below/above the threshold voltage for a period greater than or equal to ½ cycle [10]. There is a potential concern of sag/swell, over-voltage/under-voltage due to increased penetration of DG into the grid.

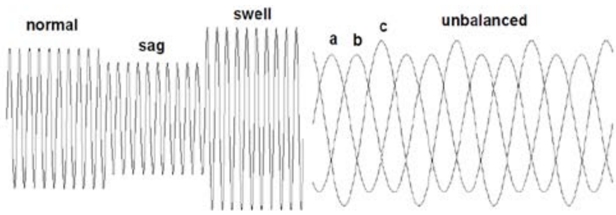

FIGURE 5 VOLTAGE SAG, SWELL AND UNBALANCE[9]

Voltage Unbalance

Voltage unbalance is regarded as a significant PQ problem at the electricity distribution level. In a balanced sinusoidal system the three phase-to-neutral voltages are equal in magnitude and phase difference from each other is 120 degree. Any difference in that magnitude and/or phase shift causes unbalanced supply as shown in Figure 5. Voltage unbalance is caused by unequal system impedances and unequal distribution of single-phase loads [11]. Operation of an induction motor above 5% voltage unbalance is not recommended by National Electrical Manufacturers Association (NEMA) of USA. There are growing concerns, as the increased penetration of single phase DG can overload one phase by unloading other phase.

Harmonics

Harmonics are the frequencies that are integer multiples of the fundamental frequency. Harmonic distortion in voltage or current waveform differs from that of an ideal sinusoidal waveform and produces waveform distortion. The cause of harmonic distortion is brought about predominantly by the

impact of nonlinear load or generating sources connected by inverters. Harmonics due to single phase distorting loads spread across the three phases and excessive level of harmonics due to single phase load/source can overload the neutral which causes overheating the neutral conductor [12]. High level of total harmonic distortion (THD) can cause thermal effects on motors, transformers and capacitors causing excessive heating and overloading of the neutral, as well as disturbance of electronic equipments. High penetration of RE in LV-DN can cause single phase loading and leads to introduce harmonics. Moreover inverters and its switching are a possible source of harmonic. Figure 6 shows harmonic distortion.

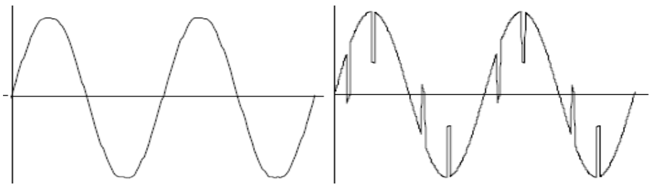

FIGURE 6 FLAT TOP AND NOTCHING HARMONIC DISTORTION[12]

THD in a current or voltage signal can be calculated using Equation 3 and 4

$$THD(i) = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \ldots\ldots + i_{n-1}^2}}{i_1} \tag{3}$$

$$THD(v) = \frac{\sqrt{v_2^2 + v_3^2 + v_4^2 + \ldots\ldots\ldots + v_{n-1}^2}}{v_1} \tag{4}$$

where i_1 and v_1 is the fundamental component of currant and voltage and i_n and v_n is the harmonic components.

Islanding

A power system island is formed when part of the network is isolated from the main grid and a local DG continues to supply power. Traditionally when network fault occurs, protection device cause the local network to de-energize. In the present condition network utilities doesn't have control over DGs and if part of the fault network remains energized by the DGs can create islanding, a serious protection and safety risk.

Notching

Notching is a periodic voltage disturbance caused by normal operation of power electronic devices when current is commutated from one phase to another. Three-phase electric switching devices such as AC to DC converters add notching as shown in the Figure 7.

FIGURE 7 NOTCHING

Voltage fluctuation and Flicker

Voltage fluctuation are systematic variations of the voltage envelop or a series of random voltage changes, but the magnitude does not normally exceed the allowable voltage range. Figure 8 shows voltage fluctuations. The magnitude of voltage may fluctuate with varying load and continuous or random fluctuations are referred as flickering. Short-term (in minutes) and long-term (a few hours) flickers can be measured by flicker meter. Fluctuation in magnitude of energy is common in PV and wind DGs.

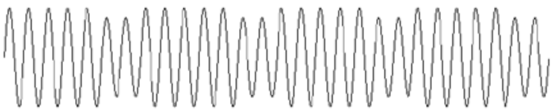

FIGURE 8 VOLTAGE FLUCTUATIONS [9]

Transient distortion

Transients are generally large, short duration voltage change usually resulting from lighting strikes or switching operations on the network. They last for less than half cycle of the main voltage cycle as shown in Figure 9. Noise is high frequency (up to about 200,000 Hz) disturbance on the voltage as shown in Figure 9.

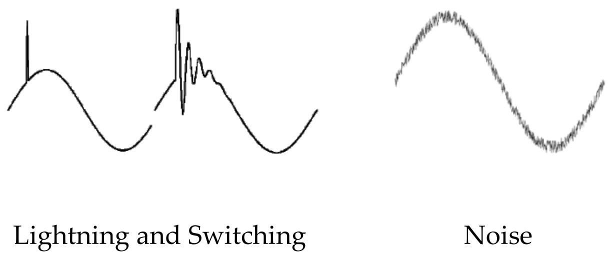

FIGURE 9 TRANSIENTS AND NOISE

DC offset

The presence of DC voltage or current in AC power is termed as DC offset.

Stability

Stability problem typically involve disturbances such

as short circuits and subsequent removal of generation or load which results in generation - load unbalance. Improper design or control may contribute to stability problem. Akatsuka Motoki et. al. [13] mentioned, fluctuation in output of megawatt class PV system may disturb stable operation of power system.

The following section describes different international and Australian standards and summarizes relevant PQ parameters.

Regulatory Standard

Recommendations have been made by the Standard Organizations for load and supply quality, defined voltage, current and frequency characteristics and also present the limit of harmonic injection. There are several standards that defined the PQ criteria to operate power network with optimum performance and to integrate RE into the grid. However, there is still some gap in harmonization among different PQ parameters in different standards to ensure PQ in different types of network, especially when DGs are connected with it.

AS 60038: Standard voltages [14]

It describes, at PCC inverter should supply nominal voltage of 230 V AC for single phase line to neutral and 400 V AC for three phase line to line with a tolerance of +10%, -6% at a frequency of 50Hz. The utilization voltage range is +10%, -11%. However, existing nominal voltage is 240/415 V AC.

For 1 kV to 35 kV three phase systems, highest voltage limit for equipment is 3.6, 7.2, 12, 24, 36 kV for nominal system voltage of 3.3, 6.6, 11, 22 and 33 kV respectively. Single wire earth return (SWER) system's nominal voltage is 12.7 and 19.1 kV derived from three phase nominal system voltages of 22 and 33 kV respectively.

For nominal voltage above 35 kV to 230 kV three phase system, highest voltage limit for equipment is 72.5, 123, 145, 245 kV for nominal system voltage of 66, 110, 132, 220 kV respectively.

AS 61000.3.100-2011: Steady state voltage limits in public electricity systems [10]:

It provides the limits of steady state supply voltage at the customer connection points.

- Steady state voltage limits for LV (230 V nominal) system and medium voltage (MV) system as give in Table 1 & 2. Voltage dip/sag and swell for LV and MV system as given in Table 3 and 4:

TABLE 1 LV STEADY STATE VOLTAGE LIMITS

Steady state voltage measure (10 minutes r.m.s)	Voltage limit (P-N)		Voltage limit (P-P)		Single phase 3 wire, centre neutral limit (P-P)	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
$V_{1\%}$	216V	-	376V	-	432V	-
$V_{99\%}$	-	253V	-	440V	-	506V

TABLE 2 MV STEADY STATE VOLTAGE LIMITS

Highest voltage for equipment (V_{max}) kV	Nominal voltage ($V_{nominal}$)	Phase-to-phase voltage limit (10 minutes r.m.s)		
		Min ($V_{1\%}$) kV	*Max ($V_{99\%}$) kV*	*Max Voltage spread ($V_{99\%}$ - $V_{1\%}$) kV*
3.6	3.3	2.97	3.50	0.33
7.2	6.6	5.94	7.00	0.66
12.0	11.0	9.90	11.66	1.10
24.0	12.7[a]	11.43	13.46	1.27
36.0	19.1[a]	17.19	20.25	1.91
24.0	22.0	19.80	23.32	2.20
36.0	33.0	29.70	34.98	3.30

a. Single wire earth return (SWER) phase-phase voltage

TABLE 3 LOW VOLTAGE DIP AND SWELL MEASUREMENT THRESHOLDS

Voltage threshold ½ cycle r.m.s.	Phase - neutral Voltage (P-N)		Phase - phase Voltage (P-P)		Single phase 3 wire, centre neutral Voltage (P-P)	
	Dip	*Swell*	*dip*	*swell*	*dip*	*swell*
	207V	262V	360V	456V	414V	524V

TABLE 4 MEDIUM VOLTAGE DIP AND SWELL MEASUREMENT THRESHOLDS

Highest voltage for equipment (V_{max}) kV	Nominal voltage ($V_{nominal}$)	½ cycle r.m.s. Voltage thresholds	
		Supply Voltage dip threshold (kV)	*Supply Voltage swell threshold (kV)*
3.6	3.3	2.84	3.6
7.2	6.6	5.68	7.2
12.0	11.0	9.46	12.0
24.0	12.7[a]	10.92	14.0
36.0	19.1[a]	16.43	21.0
24.0	22.0	18.92	24.0
36.0	33.0	28.38	36.0

a. Single wire earth return (SWER) phase-phase voltage

AS/NZS 61000.3.3:2006- Limitation of voltage change, voltage fluctuation and flicker [15]

It explains the limits for voltage fluctuations and flicker produced by the equipments (e.g. welders, motors) [15] of input current $\leq$ 16A per phase and system voltage between 220 V and 250 V at 50 Hz. It describes:

- Short-term flicker (P_{st}) value shall not be greater than 1.0
- Long-term flicker (P_{lt}) value shall not be greater than 0.65
- Relative steady-state voltage change shall not exceed 3.3%
- Voltage change shall not exceed 3.3% for more than 500 ms.

AS/NZS 61000.4.15:2012 [16] explains the testing and measurement techniques of flicker meter and evaluates P_{st} for 10 minutes and P_{lt} for 2 hours.

IEEE Std 1159-1995:IEEE recommended practice for monitoring electric power quality[8]

It provides detailed description of power quality variations and it is the recommended practice for monitoring electromagnetic phenomena that cause power quality problems. Table 5, 6, 7 shows the typical characteristics of power system electromagnetic phenomena.

TABLE 5 SHORT DURATION VARIATIONS

	Typical duration	**Typical voltage magnitude**
	Instantaneous	
Sag	0.5 - 30 cycles	0.1 - 0.9 p.u.
Swell	0.5 - 30 cycles	1.1 - 1.8 p.u.
	Momentary	
Interruption	0.5 cycles - 3s	<0.1 p.u.
Sag	30 cycles - 3s	0.1 - 0.9 p.u.
Swell	30 cycles - 3s	1.1 -1.4 p.u.
	Temporary	
Interruption	3s - 1 min	<0.1 P.u.
Sag	3s - 1 min	0.1 - 0.9 p.u.
Swell	3s - 1 min	1.1 - 1.2 p.u.

TABLE 6 LONG DURATION VARIATIONS

	Typical duration	**Typical voltage magnitude**
Undervoltage	> 1 min	0.8 - 0.9 p.u.
Overvoltage	> 1 min	1.1 - 1.2 p.u.

TABLE 7 VOLTAGE IMBALANCE AND WAVEFORM DISTORTION

	Typical duration	**Typical voltage magnitude**
Voltage imbalance	Steady state	0.5 - 2%
DC offset	Steady state	0 - 0.1%
Harmonics (0 -100th Hz)	Steady state	0 - 20%
Interharmonics (0 - 6kHz)	Steady state	0 - 2%
Voltage fluctuation (<25Hz)	Intermittent	0.1 - 7%

IEEE 1547: Standard for interconnecting distributed resources with electric power systems[17]

It provides technical specification and testing for connection of DER (capacity of 10 MVA or less) with Electric Power Systems (EPS). DER includes distributed generators (DG) and energy storage systems. The following requirements should be met at the PCC.

- DER and interconnected system shall not inject DC current greater than 0.5% of the full rated output current.
- Harmonic current injection at the PCC shall not exceed the limit given in Table 8. Even harmonics are limited to 25% of the odd harmonic limits.

TABLE 8 MAXIMUM HARMONIC CURRENT DISTORTION (%)

Harmonic order (h)	**h<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h**	**TDD**
%	4.0	2.0	1.5	0.6	0.3	5.0

- Unintentional islanding due to DER shall be de-energized within 2 seconds of island formation.
- Inverter based interconnection system to an EPS should meet the range of frequency, voltage and phase difference as shown in Table 9.

TABLE 9 SYNCHRONIZATION PARAMETER LIMITS

Rating of DR(KVA)	**Δf (Hz)**	**ΔV (%)**	**ΔΦ (°)**
0 - 500	0.3	10	20
>500 - 1500	0.2	5	15
>1500 - 10000	0.1	3	10

AS 4777-2005: Grid connection of energy systems via inverters[18]

This standard considers inverter connects RE and storage to the DN. It has three parts describing (a) installation requirements (b) inverter requirements and (c) grid protection requirements. It limits inverter ratings up to 10 kVA for single phase and 30 kVA for three phase DG units to inject electric power to the DN.

- Power flow may be either direction between energy source and grid.
- Power factor of the inverter shall be in the range from 0.8 leading to 0.95 lagging for 20% to 100% rated output.
- Harmonic currents of the inverter shall not exceed the limits shown in Table 10 and total harmonic distortion (THD) up to 50th harmonic shall be less than 5%.

TABLE 10 HARMONIC CURRENT LIMIT

Harmonic order number	Harmonic current Limits (%)
Odd harmonic	
3, 5, 7, and 9	4%
11, 13 and 15	2%
17, 19 and 21	1.5%
23, 25, 27, 29, 31 and 33	0.6%
Even harmonic	
2, 4, 6 and 8	1%
10 - 32	0.5%

- Transient voltage duration at the output of inverter shall not exceed the limit shown in Table 11.

TABLE 11 TRANSIENT VOLTAGE LIMIT

Instantaneous voltage		Duration (seconds)
Line-to- neutral (Volts)	*Line-to-line(Volts)*	
910	1580	0.0002
710	1240	0.0006
580	1010	0.002
470	810	0.006
420	720	0.02
390	670	0.06
390	670	0.2
390	670	0.6

- For single phase inverter and three phase inverter (between phase to neutral and two phases), the DC output current of the inverter at the AC terminal shall not exceed 0.5% of rated output current or 5 mA whichever is greater.
- Grid protection device shall operate within 2 seconds to avoid islanding if voltage and frequency exceeds the limit shown in Table 12.

TABLE 12 VOLTAGE AND FREQUENCY LIMITS

Voltage	Voltage limits	
	Single phase	*Three phase*
V_{min}	200 - 230V	350 - 400V
V_{max}	230 - 270V	400 - 470V
Frequency	**Frequency limits**	
f_{min}	45 - 50Hz	
f_{max}	50 - 55Hz	

Energex and Ergon Energy Standard for network performance[19]

This standard developed by Energex and Ergon Energy in Queensland, Australia to ensure reliability and power quality to the customer connected to the DN of Energex or Ergon Energy. The following PQ parameter limits are practiced:

- Voltage Regulation: Nominal voltage and maximum allowable voltage range is shown in Table 13.

TABLE 13 VOLTAGE RANGES AND MAXIMUM ALLOWABLE VARIANCE

Nominal Voltage	Maximum allowable variance
<1 kV [20] (240V Phase to Neutral 415V Phase to Phase 480V Phase to Phase)	Nominal voltage ± 6%
1 kV - 22kV	Nominal voltage ± 5%
>22kV	Nominal voltage ± 10%

- Voltage unbalance: Voltage unbalance is expressed in percentage ((Negative sequence Voltage/Positive sequence Voltage) *100%) and limit is shown in Table 14 and decided for 1 min, 10 min and 30 min averaging period.

TABLE 14 VOLTAGE UNBALANCE

Nominal supply voltage	Voltage Unbalance			
	No contingency event	*Credible contingency event*	*General*	*Once per hour*
	30 min average	*30 min average*	*10 min average*	*1 min average*
>100 kV	0.5%	0.7%	1.0%	2.0%
10 kV - 100kV	1.3%	1.3%	2.0%	2.5%
<10kV	2.0%	2.0%	2.5%	3.0%

- Neutral to Earth voltage difference: For AC line voltage difference between neutral and earth should be less than 5V at the point of supply.
- Voltage Swells: It is a temporary increase of voltage which may last from ½ cycle to 1 minute and shall not go over 10% of nominal voltage at any time.
- Voltage Sags (Dips): Voltage sag may last from ½ cycle to 1 minute. For normal operation sag shall not go under 10% of nominal voltage at any time.
- Power Frequency: Fundamental frequency for Australia is 50Hz and normal operating frequency band is 49.85 Hz to 50.15 Hz for 99% of the time.
- Voltage Fluctuation and Flicker: Compatibility level of voltage flicker on the electricity supply system for voltage up to 35 kV is given in Table 15. Flicker severity index obtained for each 2 hour period for long-term and 10 minutes period for short-term flicker.

TABLE 15 COMPATIBILITY LEVELS OF SHORT AND LONG FLICKER

	Compatibility levels
Short time flicker (Pst)	1.0
Long time flicker (Plt)	0.8

- Harmonics: The compatibility of voltage harmonics for the system voltages up to 35 kV is shown in Table 16.
- Power factor: It is the ratio of real power (kW) to apparent power (kVA). The allowable range of power factor are shown in Table 17:
- DC offset: It is the DC voltage or current in the AC power system. Neutral to earth voltage from DC source should be limited to less than 10 V.

TABLE 16 HARMONIC VOLTAGE (IN % OF NOMINAL VOLTAGE)

Odd harmonics				Even Harmonics	
Multiple of 3		*Non multiple of 3*			
Order (h)	*% voltage*	*Order (h)*	*% voltage*	*Order (h)*	*% voltage*
3	5.0	5	6.0	2	2
9	1.5	7	5.0	4	1
15	0.3	11	3.5	6	0.5
21	0.2	13	3.0	8	0.5
>21	0.2	17	2.0	10	0.5
		19	1.5	12	0.2
		23	1.5	>12	0.2
		25	1.5		
		>25	0.2+1.3(25/h)		
Total harmonic distortion (THD): 8%					

TABLE 17 POWER FACTOR PERFORMANCE RANGE

Nominal Supply Voltage	Power factor range
50kV - 250kV	0.95 lagging - 1.0
1kV - <50kV	0.90 lagging - 0.90 leading
<1kV	>0.80 but not leading

- Notching: It is the dip in supply voltage and the recommended limits for LV system (<1 kV ACrms) are following the standard [21] is shown in Table 18:

TABLE 18 RECOMMENDED LIMITS FOR NOTCHING

	Special application	General Systems	Dedicated Systems
Notch Depth	10.0%	20.0%	50.0%
Notch Area (An)*	16,400	22,800	36,500
*-Volt-microseconds at rated voltage and current			

Ergon Energy - Photovoltaic Planning Criteria[22]

In Australia, Ergon Energy, the DNSP in Queensland, developed Photovoltaic planning criteria and recommendations were made to ensure power quality and to ensure that PV system can successfully operate majority of the time. However this planning criterion did not cover harmonics and fluctuation yet. The recommended guidelines are [22]:

- PV energy system average efficiency considered 93% considering PV panel efficiency 95% and

inverter efficiency 98%.

- Distribution transformer (DT) taps should not be altered to alleviate PV energy system voltage rise and to avoid islanding in the network.
- Each installation of PV capacity restricted to 1.3 kW in rural areas for DT up to 50 kVA and in urban areas 4 kW for DT up to 100 kVA.
- The allowed voltage rise due to PV energy system at PCC is limited to 1% (240 V base).

PV connects to the network via inverters and inverters operate in such a way to maximize the power from PV panels. Therefore inverters do not have any voltage control features [22]. This mode of inverter operation causes voltage rise at the point where inverter connects to the network. This voltage rise is particularly severe in single phase PV system as voltage rise occurs in both phase and neutral conductor; as a consequence phase imbalance occurs.

Next section describes the recommendations and comments of few utility operators or experimental experiences while connecting RE DG into the grid.

Managing Renewable Energy in a Grid

Few European countries are leading in utilization of PV electricity. Austria, France, Germany, Spain, Netherlands and United Kingdom are the six countries which represent 98% of installed PV power in European Union. The technical assessments expressed about the following concerns after PV-DG integration into the grid in these countries [23]:

- Harmonic emission by inverters was considered a present and future concern for high penetration of PV.
- Voltage regulation was considered a big concern for weak grids with high PV penetration. Different regulations allowed overvoltage limits of 5% to 6% by PV plants.
- Network protection was considered a big concern as there is lack of direct control on DGs by the DNSP.
- Unintentional islanding due to high penetration of PV-DG was considered a matter of concern.
- Austria, Spain and Netherlands set PV-DG penetration limits for LV network between 33% and 75% whereas for Medium voltage (MV) network it was 50%.
- Current standards for PV-DG was considered to be improved for harmonic emission, islanding, flickering, penetration limits, interaction of multiple inverters, voltage imbalances, inverter capacitance and coordination of standard safety in LV DN.

The properties of wind turbine generators may increase the PQ related problems such as voltage fluctuation, harmonics, voltage unbalance [24]. By integrating wind turbine into the grid can introduce PQ disturbances such as:

- Due to the tower effect, fixed speed wind turbine can introduce flicker [25].
- Directly grid connected induction generator may cause heavy transients in weak distribution grids [25] and wind generators connected through electronic interface may introduce transients during switching.
- Strong wind gusts may cause simultaneous power output fluctuations by a series of wind turbines concentrated in a small area [25] and can cause frequency disturbances.
- Single phase wind generators are expected to cause voltage unbalance to some extent.
- Reactive power shortage may occur at the wind power plant which can cause voltage instability [26].
- Wind power may affect the power flow direction in the network & can cause transmission capacity problem [26].

Based on the investigation of several standards and considering the experiences of different DNSP the findings of PQ concerns are summarized below.

Results or Findings

Integrating DG such as PV, wind and storage into the LV DN may introduce voltage rise or voltage drop, flicker, fluctuations, islanding, voltage unbalance and harmonics which already experienced by different DNSP in different countries. There are few guidelines available to integrate RE into the Australian grid as discussed previously. However the current practice by local DNSP in ensuring PQ at customer end is somewhat different than the standard guideline. After thoroughly investigating the existing standards and considering the practices and planning by local utility operator to integrate RE in Queensland, Australia the

inconsistent PQ indexes are summarized below:

- **Voltage regulation:** AS-4777 indicated single phase rated voltage as 230 V with range min 200 V to max 270 V. Three phase rated voltage as 400 V with range min 350 V to max 470 V. AS-60038 indicated single phase and three phase supply voltage as 230 V and 400 V with tolerance of +10% and -6% whereas utilization range is +10% and -11%. AS/NZS-61000.3.3 indicated system voltage range as 220 V to 250 V. AS-61000.3.100 indicated single phase voltage limit as 216 V to 253 V and three phase limit as 376 V to 440 V. Ergon Energy currently practicing 240 V as single phase base voltage and Ergon-Energex combined standard stated voltage range as 240 V ±6% and 415 V ±6% for single phase and three phase respectively.
- **Frequency:** AS-4777 indicated, in 50 Hz system power frequency should not exceed limits from 45 Hz to 55 Hz, however Ergon-Energex combined standard indicated this range from 49.85 Hz to 50.15 Hz.
- **Harmonics emission:** AS-4777 indicated harmonic current limits and THD up to 50th harmonic should be less than 5%. IEEE-1547 indicated the same but for even harmonics from h>16, the limit is different. IEEE-1159 indicated harmonic voltage limit of 0~20%. Ergon- Energex combined standard stated total voltage harmonic limit (THD) to 8%.
- **Power factor:** AS-4777 indicated Power factor of the inverter shall be in the range from 0.8 leading to 0.95 lagging however Ergon-Energex combined standard stated, LV system power factor should be greater than 0.8 but not leading.
- **DC offset:** AS-4777 indicated, DC output current of the inverter shall not exceed 0.5% of rated output current or 5 mA whichever is greater. IEEE-1547 indicated DGs shall not inject DC current greater than 0.5% of rated output current. IEEE-1159 indicated DC offset voltage should be in the range of 0 ~ 0.1% of rated voltage.

The findings summarized above clearly indicates that there are gaps in different PQ parameter limits or range among different standards and guideline which can limit integrating large number of RER into the DN.

Conclusions

RE is the future source of electric energy. Storage improves the management and best utilization of RE by load shifting, minimizing intermittency and reducing fluctuations. Existing power network is not yet ready to accept bulk supply from RE sources moreover the characteristics of RE may add adverse consequences in terms of PQ in the power network especially in the LV DN. Therefore a concrete guideline should be established considering the local network condition and practices to ensure quality power to the customer. This paper investigated different international and Australian standards describing PQ and its acceptable limits. Also investigated the local DNSP’s guideline in Queensland, Australia to integrate RE into the network and found that there are few inconsistencies in practice, guideline and standards especially in voltage regulations, frequency, harmonics, power factor, dc offset as described in earlier section. AS 4777-2005 is the standard to integrate RE into the grid in Australia, however it has some inconsistencies with other standards and in current practice habits. Therefore the findings clearly indicated the discrepancies in PQ parameter limits which need to be addressed to accommodate future bulk energy from RER.

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